L2-Relaxation

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Forecast combination (Bates and Granger, 1969) is widely used in practical forecasting problems. ℓ_2-relaxation is an algorithm designed for high-dimensional forecast combinations in the presence of many forecasts. This vignette introduces the R implementation of Shi et al. (2020)'s ℓ_2-relaxation.

1 Introduction

Let y_{t+1} be an outcome variable of interest, and there are N forecasts, $\mathbf{f}_t := \{f_{it}\}_{i\in[N]}$, available at time t for y_{t+1}, where $t \in [T] := \{1, 2, ..., T\}$ and $[N] := \{1, 2, ..., N\}$. We are interested in finding an $N \times 1$ weight vector $\mathbf{w} = (w_1, ..., w_N)'$ to form a linear combination $\mathbf{w}'\mathbf{f}_t$ to minimize the mean squared forecast error (MSFE) of the estimation error

$$y_{t+1} - \mathbf{w}'\mathbf{f}_t = \mathbf{w}'\mathbf{e}_t,$$

where $\mathbf{e}_t = (e_{1t}, \ldots, e_{Nt})'$ with $e_{it} = y_{t+1} - f_{it}$.

Given the forecast error vector and its sample variance-covariance (VC) estimate $\widehat{\mathbf{\Sigma}} \equiv T^{-1}\sum_{t=1}^{T}\mathbf{e}_t\mathbf{e}_t'$, Bates and Granger (1969) proposed the following constrained minimization problem

$$\min_{\mathbf{w}\in\mathbb{R}^N} \frac{1}{2}\mathbf{w}'\widehat{\mathbf{\Sigma}}\mathbf{w} \;\text{ subject to }\; \mathbf{w}'\mathbf{1}_N = 1. \quad (1)$$

where $\mathbf{1}_N$ is an $N \times 1$ vector of ones. Denote the solution to the above constrained optimization problem as $\widehat{\mathbf{w}}^{\mathrm{BG}}$. When $\widehat{\mathbf{\Sigma}}$ is invertible, we can explicitly solve the problem to obtain the optimal solution $\widehat{\mathbf{w}}^{\mathrm{BG}} = \left(\mathbf{1}_N'\widehat{\mathbf{\Sigma}}^{-1}\mathbf{1}_N\right)^{-1}\widehat{\mathbf{\Sigma}}^{-1}\mathbf{1}_N$. The requirement of the invertibility of $\widehat{\mathbf{\Sigma}}$ is not guaranteed in high dimensional settings, and in fact $\widehat{\mathbf{\Sigma}}$ is always singular if $N > T$.

2 ℓ_2-relaxation

The *ℓ_2-relaxation primal problem* is the following constrained quadratic form optimization

$$\min_{(\mathbf{w},\gamma)\in\mathbb{R}^{N+1}} \frac{1}{2}\|\mathbf{w}\|_2^2 \quad \text{subject to} \;\; \mathbf{w}'\mathbf{1}_N = 1 \text{ and } \|\widehat{\mathbf{\Sigma}}\mathbf{w}+\gamma\mathbf{1}_N\|_\infty \leq \tau, \tag{2}$$

where τ is a tuning parameter to be specified by the user. Denote the solution to (2) as $\widehat{\mathbf{w}}$.

The following is the CVXR code.

```
rL2_primal <- function(Sigma, tau = 0) {

  N <- nrow(Sigma)
  w_gamma <- Variable(N + 1)
  w <- w_gamma[1:N]
  gamm <- w_gamma[N + 1]

  objective <- Minimize(0.5 * sum_squares(w))
  constraints <- list(sum(w) == 1,
    Sigma %*% w + gamm <= tau,
   -Sigma %*% w - gamm <= tau  )

  problem <- Problem(objective, constraints)
  result <- solve(problem, solver = "ECOS_BB")
  w_hat <- result$getValue(w_gamma)[1:N]

  return(w_hat)
}
```

The formulation is very simple. (2) can be written explicitly as

$$\begin{aligned} &\min_{(\mathbf{w},\gamma)\in\mathbb{R}^{N+1}} \frac{1}{2}\mathbf{w}'\mathbf{w} \\ \text{subject to} \;\; &\mathbf{w}'\mathbf{1}_N = 1 \\ &\widehat{\mathbf{\Sigma}}\mathbf{w}+\gamma\mathbf{1}_N \leq \tau\mathbf{1}_N, \\ -&(\widehat{\mathbf{\Sigma}}\mathbf{w}+\gamma\mathbf{1}_N) \leq \tau\mathbf{1}_N. \end{aligned}$$

The criterion function is quadratic, and there are $2N+1$ linear constraints.

The following is the Rmosek version looks more complicated, but it runs faster if the commercial convex solver Mosek is available.

```
rL2_primal_mosek <- function(Sigma, tau, tol = 1e-7) {
  N <- nrow(Sigma)
  # variable order: w_1, w_2, ..., w_N, gamma, t, s, r

  prob <- list(sense = "min")
  prob$dparam <- list(INTPNT_CO_TOL_REL_GAP = tol)

  prob$c <- c(rep(0, N + 1), 1 / 2, rep(0, 2))

  A_1 <- rbind(
    c(rep(1, N), 0), # sum of weight == 1
    cbind(Sigma, rep(1, N)) # ||Sigma_hat w + gamma||_\infty \leq tau
  )
  A_2 <- rbind(c(1 / 2, -1, 0), c(1 / 2, 0, -1)) # transformation of the squared l2 norm
  A <- Matrix::bdiag(A_1, A_2)
  prob$A <- as(A, "CsparseMatrix")
  prob$bc <- rbind(
    blc = c(1, tau * rep(1, N), 1 / 2, -1 / 2),
    buc = c(1, -tau * rep(1, N), 1 / 2, -1 / 2)
  )
  prob$bx <- rbind(
    blx = c(rep(-Inf, N + 1), 0, rep(-Inf, 2)),
    bux = rep(Inf, N + 4)
  )
  # conic constraint
  prob$cones <- matrix(list("QUAD", c(N + 4, 1:N, N + 3)))
  rownames(prob$cones) <- c("type", "sub")

  mosek_out <- Rmosek::mosek(prob, opts = list(verbose = 0))

  xx <- mosek_out$sol$itr$xx
  w_hat <- xx[1:N]
  gamma_hat <- xx[N + 1]
```

```r
  status <- mosek_out$sol$itr$solsta

  return(list(
    w = w_hat,
    gamma = gamma_hat,
    status = status
  ))
}
```

References

Bates, J. M. and C. W. Granger (1969). The combination of forecasts. *Operational Research Quarterly*, 451–468.

Shi, Z., L. Su, and T. Xie (2020). High dimensional forecast combinations under latent structures. *arXiv 2010.09477*.